Dynamic Modeling of Line Start Permanent Magnet Assistance Synchronous Reluctance by Different Rotor Designs for Industrial and Traction Applications.

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Abstract

Recent studies show that line start permanent magnet assistance synchronous reluctance (LS-PMA-SynRMs) present promising technologies because of their advantages such as simple structure and minimized amount of permanent magnet. Moreover, the LS-PMA-SynRMs can operate with direct start for net voltage or drive by power converter with torque control methods. Especially, the LS-PMA-SynRM has higher irreversible demagnetization level than IPM because it has less permanent magnet in rotor slots. This paper will develop different rotor designing and modeling of a line-start permanent magnet assistance synchronous reluctance motor (LS-PMA-SynRM) with permanent magnets arrangement in I-W-U type using both industrial and EV applications. The dynamic speed and torque performances are analyzed and compared by finite element analysis FEA. The performance of LS-PMA-SynRM is analyzed considering the position and I-W-U shape of its permanent magnet, as well as its manufacture. The proposal model of LS-PMA-SynRM has been improved efficiency, torque, and output power. Finally, the LS-PMA-SynRM with U layered magnets rotor is prototyped to verify by full efficiency map to evaluate EVs application.

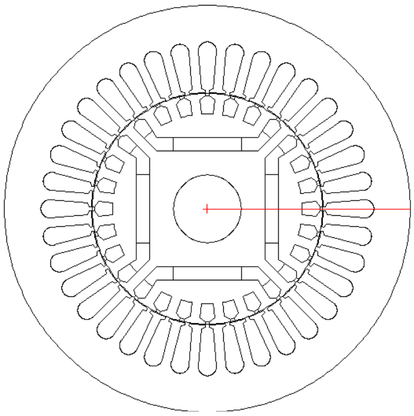
Keywords : LS-PMA-SynRM, Line Start-Permanent Magnet Assistance-Synchronous Reluctance (LS-PMA-SynRM), Fenite Element Analysis-FEA.

1. INTRODUCTION

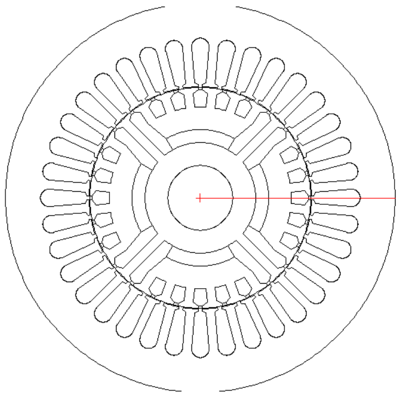
Currently, induction motors (IMs) account for 70% of industrial motors because of their simple structure and low manufacture cost. However, IMs have the secondary copper loss that limits the improvement in their efficiency. Therefore, to replace IMs, new types of motor are being studied to improve the efficiency such as line-start permanent magnet synchronous motors (LS-SynRMs) or line start permanent magnet assistance synchronous reluctance (LS-PMA-SynRMs). When LS-SynRMs and LS-PMA-SynRMs are operated at a synchronous speed, the secondary copper loss is eliminated so the efficiency can improve significantly. To save energy, use less rare-earth materials, and decrease the cost in terms of material and manufacturing processes LS-PMA-SynRMs is a good choice. A comprehensive study on line start permanent magnet assistance synchronous reluctance (LS-PMA-SynRMs) is developed for direct start or torqure control method by power inverters. This study shows that the LS-PMA-SynRM has less rare-earth materials, low cost, comparable constant-power speed range, maximum torque per ampere, and efficiency of SynRMs. In particular, LS-PMA-SynRMs have an interesting choice in electric traction and more-electrical aircraft applications because they has a special flux barrier and magnet arrangement to improve constant torque in wide range speed and less risk of irreversible demagnetization in short circuit and over heat temperature.

2. ELECTROMAGNETIC DESIGN OF LS- PMA-SYNRM

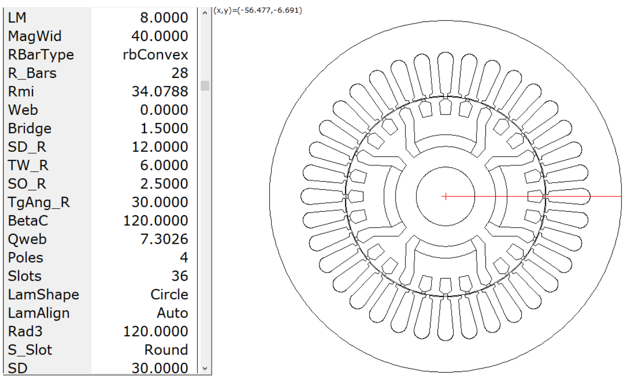
Electromagnetic design of LS-PMA-SynRM, 4-pole are designed as Figure 1. The stators of LS-PMa-SynRM has 36 slots, three types of the rotor with 28 bars. Magnetic material and silicon steel are NdFE42 and 35A350.



(a) I Shape



(b) W shape



c) U shape

Figure 1. LS-PMA-SYNRM topologies

The numbers of slot and poles, stack length, the diameter of stator and rotor, the air-gap length listed in table 1 is designed for the direct voltage of 380 VAC. The geometry parameters of stator and rotor can be calculated by estimation equation. Analytical model was undergone many calculation steps to define basic parameters. Based on torque volume density TVR from 25 to 40 kNm/m3. if we assume rotor diameter equal to rotor length, the rotor diameter D and length L sizes of LS-PMa-SynRM is determined as follow:

$$T = \frac{\pi}{4}.D^2.L_s.TRV \qquad (1)$$

With :

T : Electromagnetic torque (N.m).

D : Out diameter (m).

LS : Length of core (m).

TVR : Torque and volume ratio (kWm/m3).

In general, the design process of LS-PMA-SYNRM is similar to that of induction motor. The main parameters (such as outer diameter, rotor diameter, motor length, stator slot, airgap length) are defined by considered some practical factors with desired input requirements.

The main part of the process is to design the rotor configuration which is embedded permanent magnet. The PM configuration needs to create sufficiently magnetic voltage for magnetic circuit. In fact, there are some possible configurations sorted by the shape and position of PM inside rotor as listed below:

Table 1. Geometry parameter of LS- PMA-SYNRM

Parameters	**Values**	**Unit**
Slot Number	36	
Outer Stator	210	mm
Inner Stator	132	mm
Tooth Width	5	mm
Slot Depth	19	mm
Motor Length	180	mm
Stator Lam Length	180	mm
Magnet Length	150	mm
Magnet size	5x2	mm
Air gap	0.4	mm
Turn per coil	20	

Table 1 shows the design parameters of LS-PMA-SynRM of pole, slot, and stack length. Figure. 2 shows the rotor topology of the proposed PMA-SYNRM machines. As shown, the proposed machine is installed U-shape magnet arrangement.

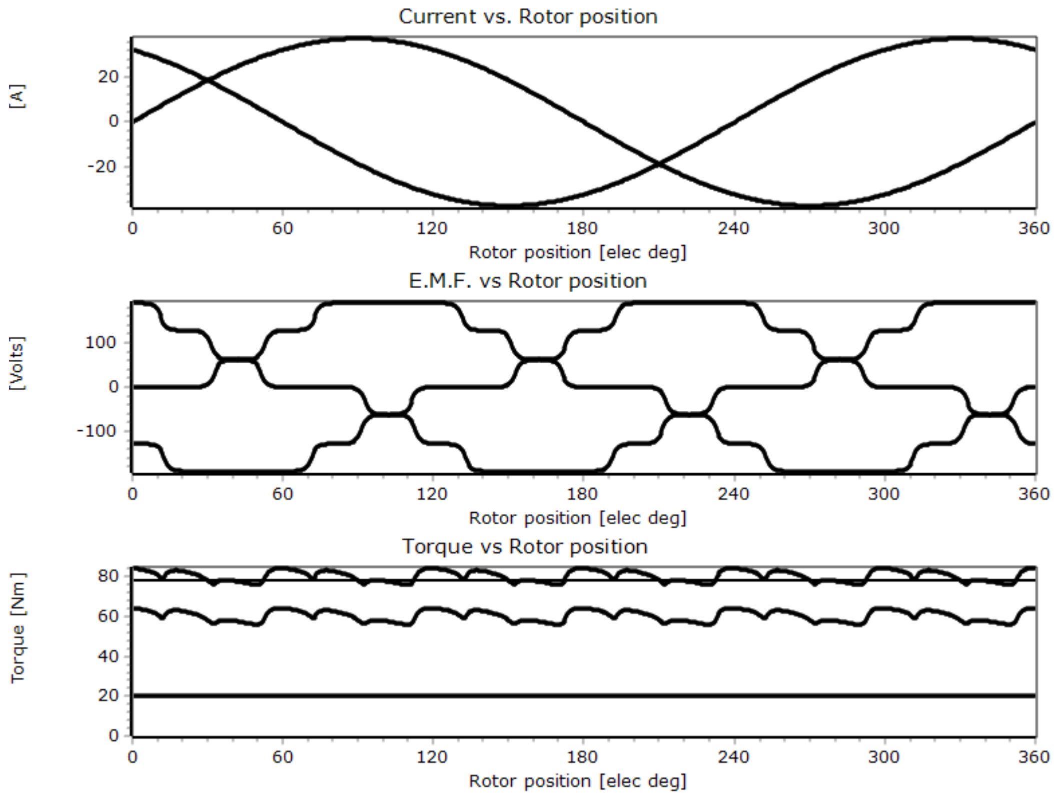


Figure 2 The current, back EMF and torque of LS- PMA-SYNRM

The back EMF at 1500 rpm with direct start is small value of 120V because the flux barriers is quite big and less permanent magnet assistance. To achieve limit DC link voltage of 450 VDC, the maximum speed can exceed to 6000 rpm with power inverter modes.

To maximize reluctance torque, amount of PM is limited. The arrangement of the PM is regarded as requisite for efficient operation in I-W-U shape. Three shapes of prototype model are simple and easy to mass production. The total weight of magnet segment and copper winding are almost the same. The cost of magnet is minimized due to expensive. Table 2 shows material Weight of PMA-SYNRM.

Table 2. Geometry parameter of LS- PMA-SYNRM

Parameter	**LS-PMA-SynRM (kg)**
Stator Lam (Back Iron)	8.26
Stator Lam (Tooth)	5.245
Stator Lamination [Total]	13.5
Armature Winding [Active]	4.138
Armature EWdg [Front]	1.027
Armature EWdg [Rear]	1.027
Armature Winding [Total]	6.193
Rotor Lam (Back Iron)	5.37
IPM Magnet Pole	4.833
Rotor Lamination [Total]	10.74
Magnet	0.5
Total	33.98

The summarized data of two models are shown in Table 3, which include of average torque, torque ripple. The power, total losses, cogging torque and efficiency under the maximized constant torque control method. The total iron losses consist of core loss and magnet eddy-current loss. The total iron loss of the model A with four-segmented magnets in V-I shape is the lowest. Therefore, the model A with four-segmented magnets is selected as the prototype machine.

3. LS-PMA-SYNRM PERFORMANCE IN DIRECT START AND TRACTION

The proposed PMA-SYNRM machines are designed and analyzed in traction. The total torque and efficiency are important performance for those motors.

Table 2. Efficiency comparison of LS-PMA-SynRM

LS-PMa-SynRM Parameter	**I shape**	**W shape**	**U shape**	**Unit**
Shaft Torque	53.67	54.267	55.667	Nm
Input Power	9123.3	9213.4	9273.3	Watts
Output Power	8644.1	8474.3	8744.1	Watts
Total Losses (on load)	519.5	522.1	529.15	Watts
System Efficiency	93.24	94.3	94.68	%
Armature DC Copper Loss (on load)	340	340	340	Watts
Magnet Loss (on load)	178.8	168.3	168	Watts
Stator iron Loss [total] (on load)	10.33	10.33	10.33	Watts
Phase Terminal Voltage (rms)	289.1	289.1	289.1	Volts
Harmonic Distortion Line-Line Terminal Voltage	4.89	4.289	3.089	Volts
Harmonic Distortion Phase Terminal Voltage	13.7	12.2	11.27	%
Back EMF Line-Line Voltage (peak)	111	112	114	%

The electromagnetic torque of an PMA-SYNRM machine is formed from two components of magnetic torque and reluctance torque. The PM component is produced based on interaction between air-gap magnetic field and armature reaction magnetic field and the reluctance component is instead on asymmetry between the PMA-SYNRM machines magnetic circuit of d-axis and q-axis. The electromagnetic torque can then be defined as:

$$T\_em = \frac{3.p}{2}\left[\lambda_{pm}.i_d + (L_d - L_q).i_d.i_q\right] \quad (3)$$

The λpm depends on magnet sizes, the q-axis inductance and d-axis inductance for PMA-SYNRM machines are calculated based on rotor magnet barrier and magnet pole U shape.

where λ_{PM} is the flux linkage generated by PM field and λd is the d-axis flux linkage generated by armature reaction field between rotor and stator. The FEA-calculated d- and q-axis inductances are shown in Figure 3. The DC link voltage of the power inverter to the PM machine is limited by the maximum bus voltage of batteries. The angular speed of the rotor is limited by the amplitude of the phase voltage. Dynamic torque of reluctance and permanent magnetic parts are shown in figure 3.

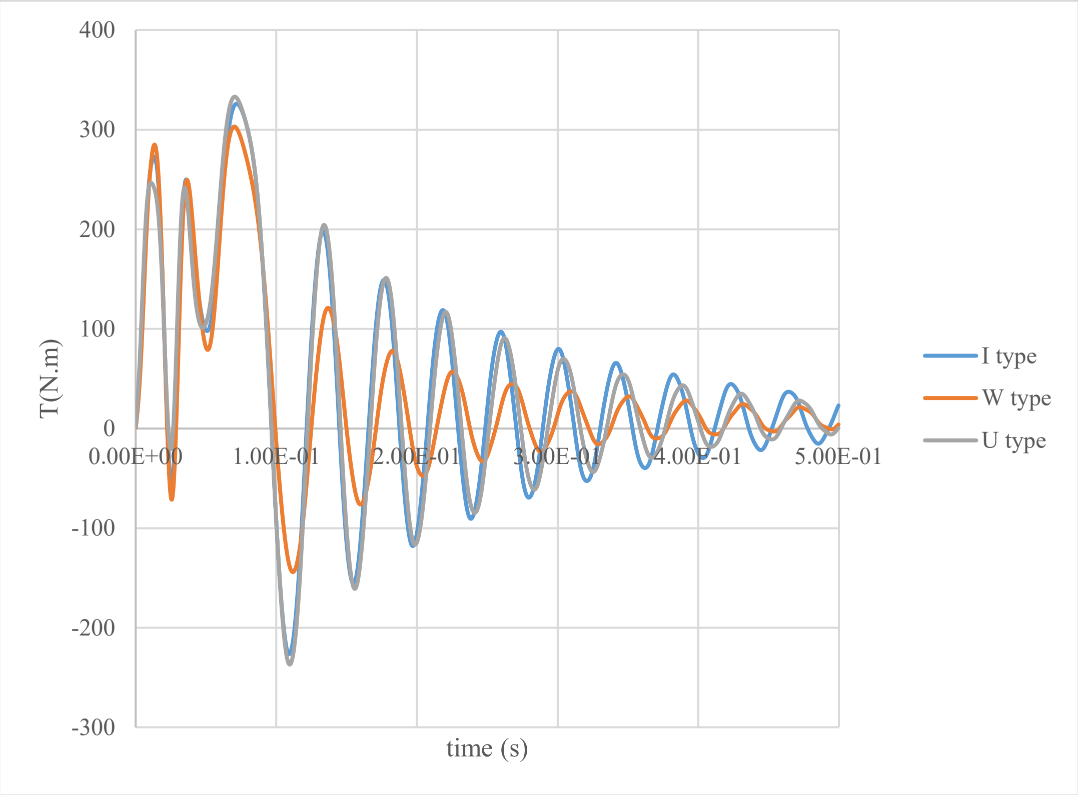


Figure 3. Dynamic starting torque comparison of I-W-U

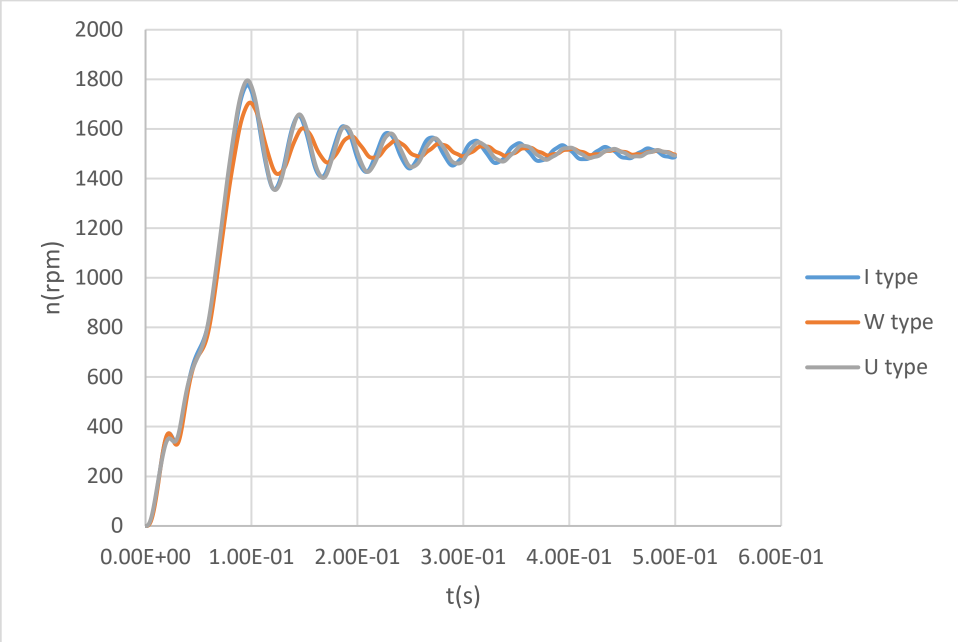


Figure 4. Dynamic starting speed comparison of I-W-U

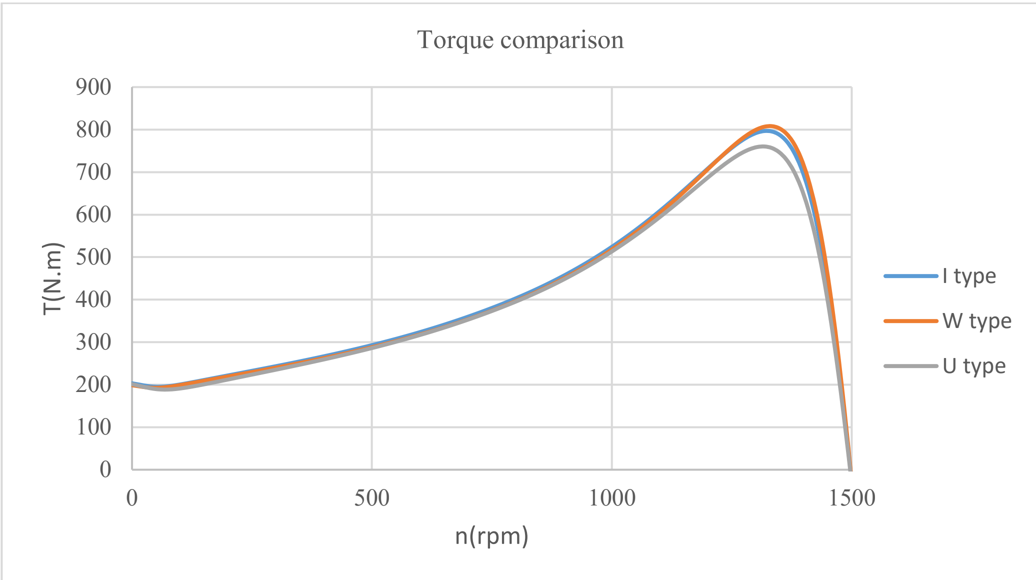


Figure 5. Dynamic starting torque vs speed comparison of I-W-U

The peak torque and power versus speed characteristics of U shape LS_PMA-SYNRM machine have been verified at 1500 rpm. With the increase of phase current density up to 5 A/mm2, the average torque is 52 Nm. The torque and power performance. Maximum efficiency is 94%. Total losses of iron cores, copper windings have been applied to thermal simulation and temperature results as below table. Temperature distribution of stator, rotor, winding, and magnet were calculated in figure 6. Maximum temperature of winding is 90.7^{o}C much lower than isolation class H (180^0). Temperature of magnet is 88 ^{0}C and detail values of other parts are listed as table 2.

Table 3. Temperature of LS- PMA-SYNRM

No	Component	LS- PMA-SYNRM T (^{0}C)
1	T [Ambient]	40
2	T [Housing - Active]	78.717
3	T [Stator Lam (back iron)]	84.833
4	T [Stator Surface]	88.403
5	T [Rotor Surface]	88.65
6	T [Airgap Banding]	88.651
7	T [Magnet]	88.197
8	T [Airgap Banding]	88.651
9	T [Rotor Lamination]	87.674
10	T [Shaft - Center]	87.375
13	T [Active Winding Minimum]	87.352

LS-PMA-SynRM temperature of rotor parts are cooler the temperature of induction motor in table 3 and stator and winding are similar to LS-PMa-SynRMs.

For traction application, the peak torque and power versus speed characteristics of U shape LS_PMA-SYNRM machine have been verified to maximum speed of 6000 rpm. With the increase of phase current density up to 10 A/mm2, the peak torque is 300 Nm. The torque and power performance. Maximum efficiency is 94%.

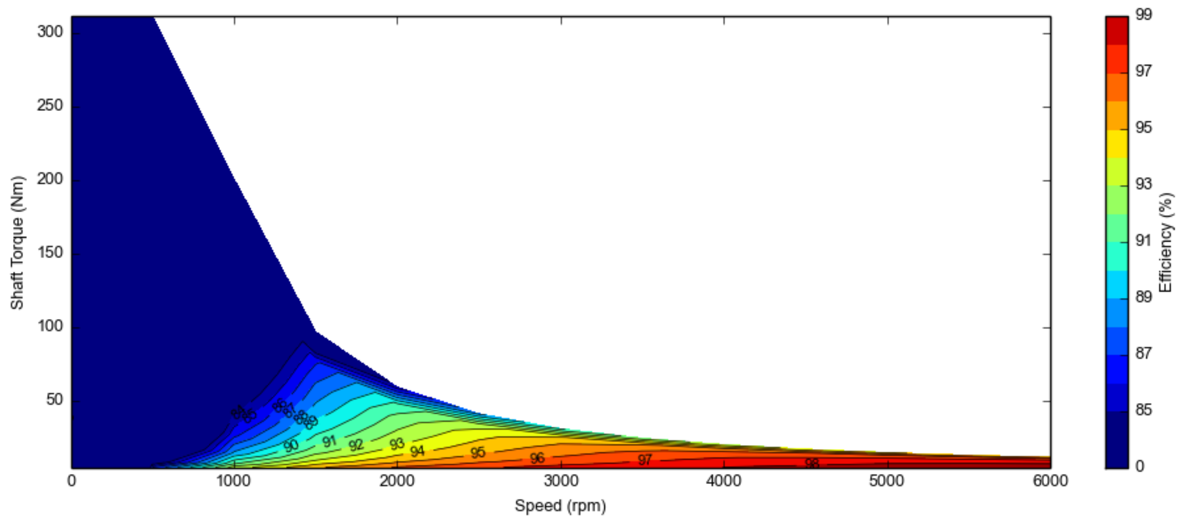


Figure 6. Dynamic starting torque vs speed map of U shape design

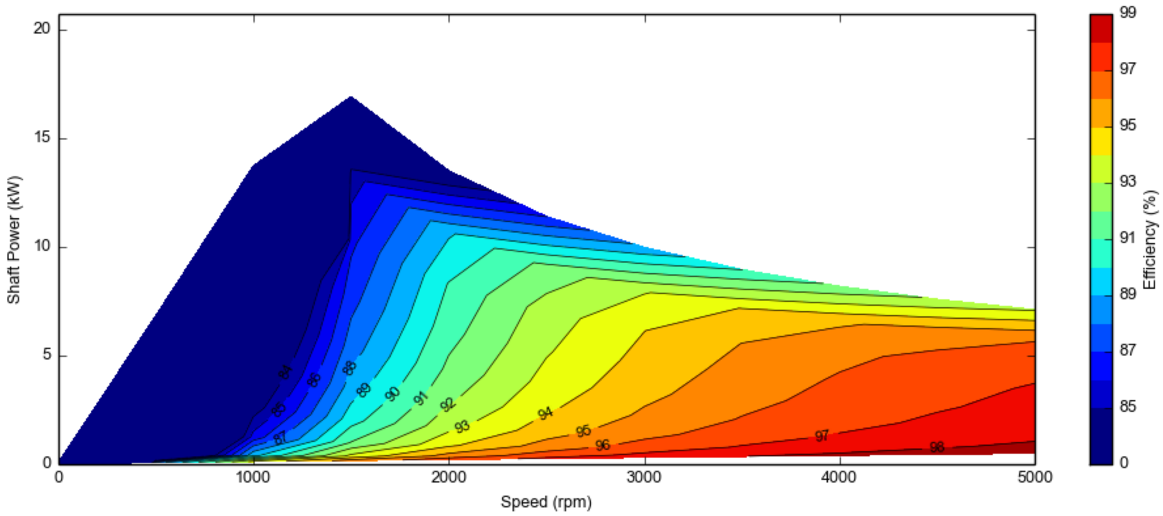


Figure 7. Output power vs speed map of U shape

Even though, the LS-PMA-SynRM is pre-determined by 11kW under direct start, if this motor works with power inveter, the maximum power is double time and peak torque is about 300 N.m.

4. CONCLUSIONS

This paper has analyzed and compared the electromagnetic performance of three multi-layered LS_PMA-SYNRM machines for industrial and traction applications. The U shape has the lowest volume of magnets and high torque and power density. Under dynamic operation, the 2U shape-LS-PMA-SYNRM machine has the short starting time to constant speed in comparison with I and W shapes. To verify the proposed design in traction application, full map of torque, power, and efficiency performances have been evaluated with limit temperature rises. The back EMF have been analyzed based on the FEA modeling to verify maximum speed. Thermal simulation was implemented to validate overheat capacity.

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